



Half-life of the 830.2 keV isomer in ^{97}Sr

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The half-life of the 830.2 keV isomeric state in ^{97}Sr , for which very different values are reported in the literature, has been measured. The experiment performed at the LOHENGRIN fission-fragment separator consisted of two independent measurements. The two measurements provided consistent results. The weighted average value, $T_{1/2} = 526(13)$ ns, supports the interpretation of the 830.2 keV state in ^{97}Sr , as the $9/2^+[404]$ neutron-hole configuration.

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Recently we reported on the first observation [1] of the $9/2^+[404]$ neutron orbital in the mass $A \sim 100$ region, which was found in ^{99}Zr . It has been pointed out [2] that the effect should be present in a number of adjacent nuclei from a given region. Indeed, shortly afterwards the $9/2^+[404]$ band was also reported in ^{97}Sr [3] and in ^{101}Zr [4]. The effect was thus confirmed, though some doubts were left, concerning the half-life of the $9/2^+[404]$ level in ^{97}Sr . The $9/2^+[404]$ band in ^{97}Sr is shown in Fig.1 to assist further discussions.

The characteristic property of the $9/2^+[404]$ configuration is K-isomerism, which is due to the large K value of the $9/2^+[404]$ orbital. In ^{97}Sr rather different half-life values of the $9/2^+[404]$ level were reported. Previous measurement of the half-life of the 830 keV isomeric level in ^{97}Sr , performed at mass separator, provided value of $T_{1/2} = 515(15)$ ns [5]. In Ref. [3] this result was questioned, however, and a half-life of $T_{1/2} = 265(27)$ ns, obtained with a nonstandard technique, was reported. We note that the half-life of 430(30) ns, reported in Ref. [6] may represent a mixed result for the 830 keV and 308 keV levels, since it was obtained from the time-delayed spectrum of the 141 keV transition, depopulating the 308.1 keV level. In our reinvestigation of ^{97}Sr [4] we could not measure any half-life because of a strong contamination by a short-lived isomer in ^{134}Te , the decay of which involves γ rays of 205 keV and 522 keV, identical to those seen in ^{97}Sr .

It is important to clear the above discrepancies, in order to provide a reliable half-life value of the $9/2^+[404]$ isomer for further discussions. In the present work we report on two new, independent measurements of the half-life of the 830 keV isomeric state in ^{97}Sr .

The ^{97}Sr isotope was produced by thermal-neutron induced fission in a $280 \mu\text{g}/\text{cm}^2$ target of ^{239}Pu placed inside the high-flux reactor at the ILL Grenoble. Fission

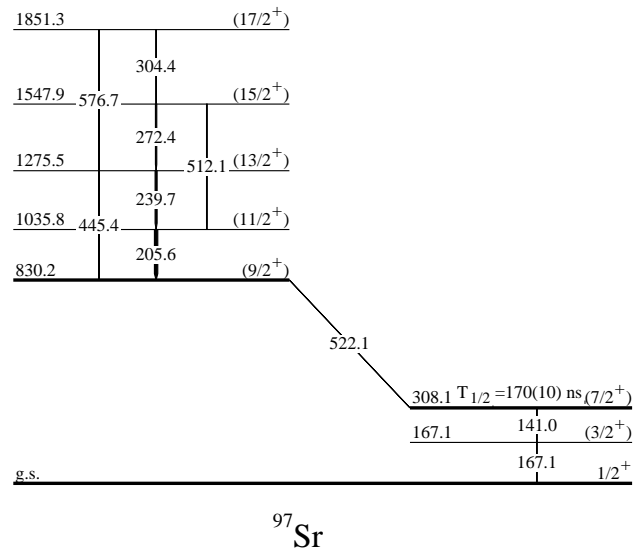


FIG. 1. The neutron $9/2^+[404]$ band in ^{97}Sr and its decay. Energies of transitions depopulating the 830.2 keV isomer are as observed in the present work. Energies of transitions above the isomer are taken from Ref.[4].

fragments, flying freely from the target, were separated using the LOHENGRIN fission-fragment separator [7]. The time of flight from the source through the separator was about $1.8 \mu\text{s}$. The fragments were detected using an ionization chamber, placed after the separator, and stopped at the end of the chamber. Isomeric γ rays were observed at this position, using two germanium detectors placed in a close geometry. To obtain the half-lives of isomeric states in fission-fragments we measured time intervals between the passing of a fission fragment through the chamber and the registration of the γ ray depopulating the isomeric level. Two independent measurements were performed, one using analog electronics and a simple chamber, as used in many previous measurements, and another using digital electronics and a chamber providing good mass resolution.

In the measurement with the analog electronics γ rays were registered within a fixed-length time window of $40 \mu\text{s}$, opened by a signal from the ionization chamber. All γ rays registered within such a time window constituted a coincidence event. Coincidence events, stored during the experiment were sorted off-line to obtain various gamma and time-delayed spectra.

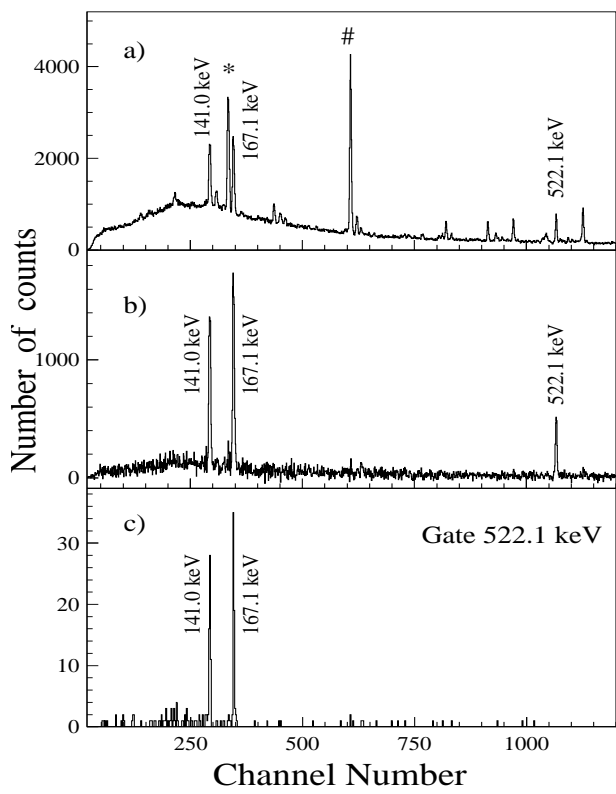


FIG. 2. Spectra of γ rays measured in the experiment with analog electronics. Fig. 2a shows the projection of γ rays measured within $5 \mu\text{s}$ time window. Symbols * and # denote lines from β^- decay of ^{97}Y and ^{102}Nb , respectively. Fig. 2b shows a spectrum where long-lived contamination and background lines were subtracted. Fig. 2c shows a spectrum of events from Fig. 2b, gated on the the 522.1 keV line.

A total projection of γ rays measured within the first $5 \mu\text{s}$ after the registration of the corresponding ion is shown in Fig. 2a. The spectrum is dominated by contamination lines from β^- decays of ^{97}Y and ^{102}Nb , marked in Fig. 2a with * and # symbols, respectively (the ^{102}Nb ions are present in the fission-fragment beam because their ionic charge is 21, hence their mass-to-charge ratio is very similar to that for ^{97}Sr ions with charge 20). In Fig. 2a there are also background lines from the surrounding materials.

To remove these contamination lines we created a “background” spectrum of γ rays measured in the last $5 \mu\text{s}$ of the $40 \mu\text{s}$ experimental time window. In such a “background” spectrum one expects the presence of contamination lines and no lines originating from microsecond isomers. Fig. 2b shows a difference of the spectrum from Fig. 2a and the “background” spectrum. In Fig. 2b the lines corresponding to short half-lives are now clearly visible. One observes three lines corresponding to transitions depopulating the 830.2 keV isomer in ^{97}Sr . Their assignment to the isomeric cascade in ^{97}Sr is demonstrated in Fig. 2c, which shows a coincidence spectrum gated on the 522.1 keV line, where only the 141.0 keV and 167.1 keV lines are seen.

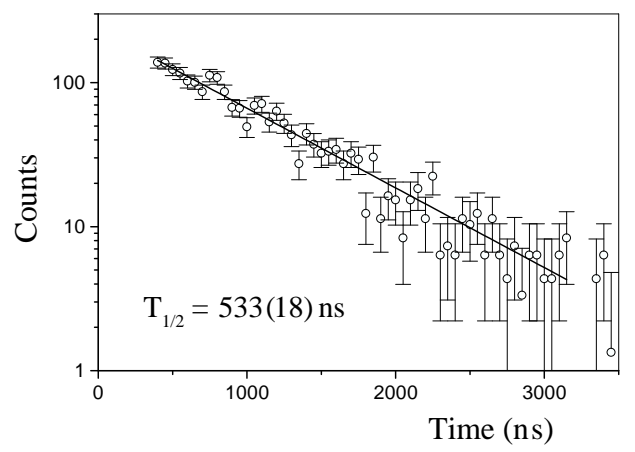


FIG. 3. Time-delayed spectrum gated on the 522.1 keV γ -ray as obtained in the measurement with the analog electronics. The thick, solid line represents the fit of an exponential-decay curve to the data.

Fig. 3 shows a time-delayed spectrum corresponding to the 522.1 keV isomeric transition. The thick, solid line represents the fit to the data of an exponential-decay curve. The half-life obtained from this fit is $T_{1/2} = 533(18) \text{ ns}$.

The second measurement of the half-life of the 830.2 keV isomer in ^{97}Sr was performed using a digital electronics. A high-resolution ionization chamber used in this run consisted of two sectors, 9 cm and 6 cm long, filled with isobutane gas and separated by a grid. Anodes mounted in both sectors provided $\Delta E1$ and $\Delta E2$ signals, respectively. Signals from the anodes provided a unique identification of incoming fragments. The resolving power of the chamber is illustrated in Fig. 4, showing the $\Delta E1 + \Delta E2$ vs $\Delta E2$ diagram. The parallelogram, drawn by a thick line in Fig. 4, marks the region corresponding to ions with mass $A=97$.

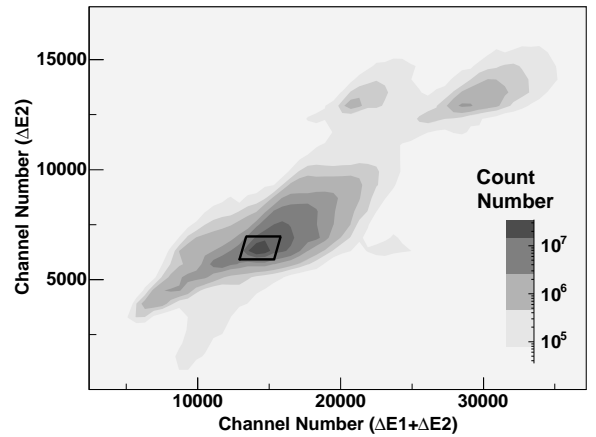


FIG. 4. The $\Delta E1 + \Delta E2$ vs $\Delta E2$ spectrum from the ionization chamber, illustrating the resolving power of the chamber. The region corresponding to mass $A=97$ ions is marked by a parallelogram.

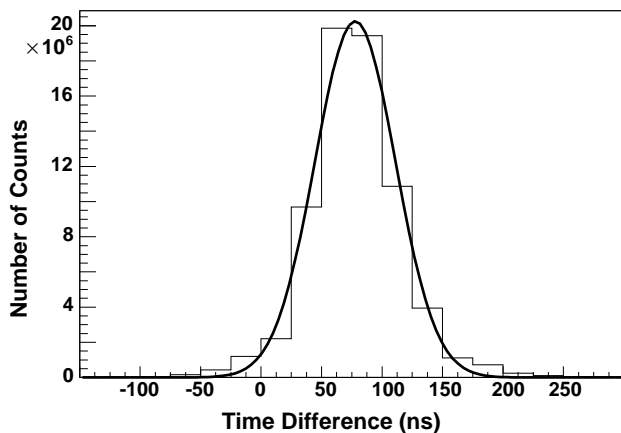


FIG. 5. The distribution of the time difference between the $\Delta E1$ and the $\Delta E2$ signals from the ionization chamber. The standard deviation for the Gaussian shape fitted to the distribution is $\sigma=33$ ns.

Fission fragments were stopped at the end of the chamber, where γ rays from these fragments were detected by two HPGe detectors in close geometry. All signals from the chamber and Ge detectors were marked with time stamps from the real-time clock running at 40 MHz (25 ns time stamp). Time-coincidence correlations between ions and γ -rays were made during the off-line analysis. For each γ ray an event was produced containing information about its energy and the time of registration relative to the arrival of the associated fragment, defined by the passing of a fission fragment above the first anode. All events were sorted in order of increasing time-stamp values. Then the correlation was made between $\Delta E1$ and $\Delta E2$ signals, corresponding to the passing of a single fragment by applying a narrow time window of 150 ns to define this coincidence. This prevented accidental coincidences between ΔE signals corresponding to the passing of two different fission fragments through the chamber (the intensity of the beam was about 2000 fission fragments per second).

In Fig.5 we show the spectrum of time difference between $\Delta E1$ and $\Delta E2$ signals from the chamber with a Gaussian shape fitting the experimental points. The standard deviation of this distribution, $\sigma=33$ ns, reflects both the time resolution of the chamber and the timing properties of our digital acquisition system. We conclude that the experimental uncertainty of the registration time of a fragment is about 10 times less than the expected half-life and neglected it in further analysis.

Fig.6a shows a γ -ray spectrum correlated with mass $A=97$ nuclei, gated on the $\Delta E1+\Delta E2$ vs $\Delta E2$ histogram on the mass $A=97$, as marked in Fig.4. The spectrum, which was sorted with a $5 \mu s$ time gate, as in the first experiment, is similar to the one displayed in Fig.2a, showing high background from the surrounding materials and β^- decays of the mass-separated beam (the ^{102}Nb ions are not present, however since in the second experiment we collected ^{97}Sr ions with charge 21).

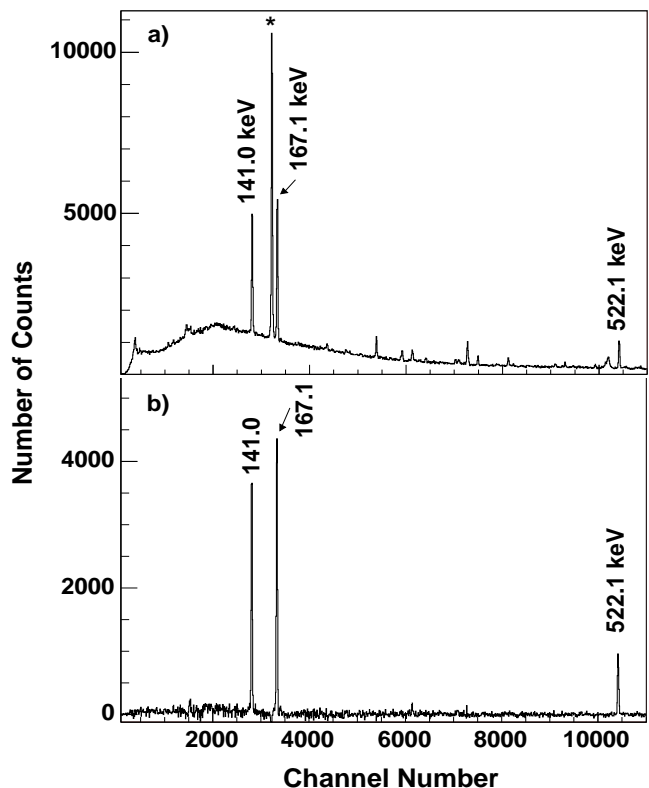


FIG. 6. γ -ray spectra obtained in the measurement using the digital electronics. The spectra are gated on signals from the ionization chamber, which corresponded to mass $A=97$ ions. Symbol * marks lines corresponding to β^- decay of ^{97}Y . Spectrum a) was sorted with time gate of $5 \mu s$. Spectrum b) was obtained from spectrum a) by subtracting a “background” spectrum, sorted with a time gate extending from $35 \mu s$ to $40 \mu s$ past the registration of an ion.

Fig.6b shows a spectrum obtained from that in Fig.6a by subtracting a “background” spectrum, which contains, as in the first experiment, γ rays measured within a $5 \mu s$ time window extending from $35 \mu s$ to $40 \mu s$ after the registration of an ion. Only the three lines at 141.0 keV, 167.1 keV and 522.1 keV are seen, corresponding to the cascade depopulating the 830.2 keV isomer in ^{97}Sr .

The time-delayed spectrum for the 522.1 keV line was produced in a following way. All γ rays registered within $5 \mu s$ after the arrival of a fission fragment were assigned to that fragment. From such events we sorted the time-delayed spectrum, corresponding to the 522.1 keV isomeric line, which is shown in Fig.7 (we show the same range from 0 to $3.5 \mu s$ as in Fig.3). The spectrum is background-subtracted, i.e. from the spectrum gated on the 522.1 keV line we subtracted a spectrum gated on the flat background next to the 522.1 keV line. The background subtraction is rather complete since a fit to the constant background gives zero within error bar. This confirms that the 830.2 keV isomer is populated directly in the fission process and the 522.1 keV line does not contain any contribution from β^- decay.

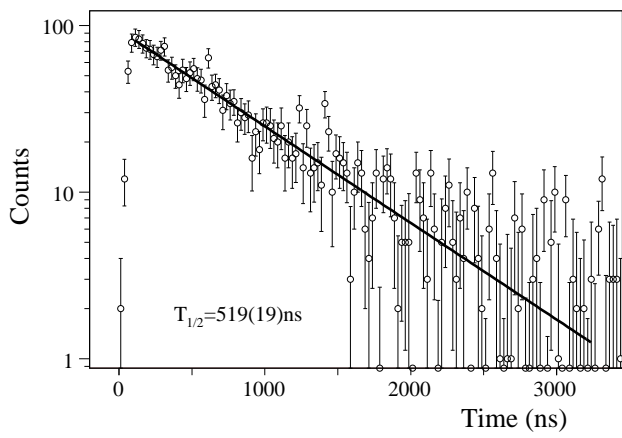


FIG. 7. Time-delayed spectrum corresponding to the 522.1 keV transition in ^{97}Sr . Each channel is 25 ns wide. The rise of the spectrum in the first four channels (0 - 100 ns) is due to time response function of the experimental setup.

The half-life of the 830.2 keV isomer in ^{97}Sr was obtained by fitting the exponential decay curve to the time-delayed spectrum shown in Fig.7. The fit region in Fig.7 was selected to avoid the first 100 ns, where a rise is seen due to the finite time resolution of the experimental setup. The rise is dominated by the width seen in Fig.5 (each point in the histogram corresponds to a 25 ns time bin). We also neglected this finite resolution in further analysis due to its low value, compared to the measured half life (i.e. no corresponding unfolding was made). The fit shown as a solid line in Fig.7 corresponds to $\chi^2=1.05$ per degree of freedom. The half-life resulting from this fit is $T_{1/2}=519(19)$ ns.

In both experiments we used the 522.1 keV, isomeric transition only to determine the half-life of the 830.2 keV isomer, to avoid uncertainties due to contamination in the 141.0 keV and 167.1 keV lines from β^- decay as well as due to the 170 ns half-life of the 308.1 keV level.

The half-life obtained from the data measured with the digital electronics is consistent with the result from the experiment with the analog electronics. The weighted average from both measurements, $T_{1/2}=526(13)$ ns agrees very well with the result of Ref. [5]. The new half-life is clearly different from the $T_{1/2}=265(27)$ ns half-life reported in Ref. [3].

Due to a strong similarity between the structure of ^{97}Sr and its isotone ^{99}Zr one could expect that the hindrance factors associated with the decay of the $9/2^+[404]$ isomer should be similar in ^{97}Sr and ^{99}Zr . Therefore, half lives of $9/2^+[404]$ isomers in these nuclei should approximately scale with the energy of the isomeric transition. Taking the half-life of the $9/2^+[404]$ level in ^{99}Zr [1] one estimates in this way the half-life in ^{97}Sr to be 635(120) ns (see Ref. [4]). The $T_{1/2}=526(13)$ value obtained for ^{97}Sr in the present work supports the interpretation of the 830.2 keV state in ^{97}Sr , as the $9/2^+[404]$ neutron-hole excitation, analogous to that observed in its isotone ^{99}Zr .

TABLE I. Hindrance factors, H, for the 522.1 keV, 786.8 keV and 710.0 keV transitions deexciting $9/2^+[404]$ isomeric level to the $7/2^+$ level in ^{97}Sr , ^{99}Zr [Ref.1] and ^{101}Zr [ref.4], respectively.

E_γ [keV]	Multipol.	$T_{1/2}^{part.}$ [ns]	T_w [s]	H
522.1	M1	526(13)	$1.6 \cdot 10^{-18}$	$3.3 \cdot 10^6$
522.1	E2	526(13)	$5.5 \cdot 10^{-10}$	956
786.8	M1	186(35)	$4.6 \cdot 10^{-14}$	$4.0 \cdot 10^6$
786.8	E2	186(35)	$6.7 \cdot 10^{-11}$	2780
710.0	M1	47(6)	$6.5 \cdot 10^{-14}$	$7.2 \cdot 10^5$
710.0	E2	47(6)	$1.1 \cdot 10^{-10}$	427

Table 1 shows hindrance factor, H, for the $9/2^+ \rightarrow 7/2^+$ decay branch of the $9/2^+[404]$ isomer in ^{97}Sr , ^{99}Zr [1] and ^{101}Zr [4], with energies 522.1 keV, 786.8 keV and 710.0 keV, respectively, calculated for both, M1 and E2 limits (mixing ratios are not known for these M1+E2 transitions). In ^{101}Zr , the $9/2^+[404]$ isomer decays to the $3/2^+[411]$ deformed band. The degree of K-forbiddenness, which is two for the M1 and one for the E2 transition, is consistent with hindrance factors observed for K isomers involving the $9/2^+[404]$ orbital [9]. In case of ^{97}Sr and ^{99}Zr the $9/2^+[404]$ isomer decays to the spherical $g_{7/2}^+$ configuration, for which K is not defined, complicating comparisons with ^{101}Zr . The H values in ^{97}Sr and ^{99}Zr are similar and are a few times higher than in ^{101}Zr .

Based on the observed similarities between $9/2^+[404]$ isomers in ^{97}Sr and ^{99}Zr one may predict $9/2^+[404]$ isomers in other N=59 isotones. An extrapolation of the energy trend of isomeric transitions in ^{97}Sr and ^{99}Zr to ^{101}Mo suggests the energy of the isomeric transition in excess of 1 MeV and a partial half-life of about 100 ns. It is likely, however, that the $9/2^+[404]$ isomer in ^{101}Mo , expected at about 1.5 MeV, will have branchings to other levels with spin 9/2 and the half-life will be shorter. On the other hand, in the ^{95}Kr nucleus the expected energy of the isomeric transition is about 400 keV and the partial half-life should be about a microsecond.

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